

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

Vol. 7, Issue 9, September 2018

Implementation of Solar-To-Fuel Conversions in Achieving Performance by Nanotechnology

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ABSTRACT: One of the greatest difficulties for humanity in the era of 21 is utilization of elective hotspots for Non-renewable, restricted fossil fuels that hugely contribute on the issue of global warming. In this test, solar energy generation is quickly turning into a crucial wellspring of renewable energy being created as an other option to conventional wellsprings of intensity. For enhancing the proficiency of solar gadgets different methodologies was proposed yet nanotechnology, a blend of science and designing, is seen as new possibility for clean energy applications. Nanotechnology will convey noteworthy advantages to the energy area, particularly to energy stockpiling and solar energy. Enhanced materials productivity and lessened assembling costs are only two of the genuine financial advantages that nanotechnology as of now brings these fields.

The global demand for energy is expanding and the unfavorable results of rising ozone harming substance emissions, global warming and natural corruption show real difficulties. Solar energy offers a perfect and practical renewable energy source with the possibility to mitigate the inconvenient results ordinarily connected with fossil fuel-based energy age. Since nanofluids offer considerably more prominent warmth retaining and warm exchange properties contrasted with conventional working fluids. The survey outlines ebb and flow inquire about in this inventive field. It examines coordinate solar absorber gatherers and techniques for enhancing their performance.

KEYWORDS: Solar Energy, Nanotechnology, Renewable and Sustainable Energy

I. INTRODUCTION

Nanotechnology

Nanotechnology is a field of research and advancement concerned about building 'things' - by and large, materials and gadgets - on the size of iotas and particles. A nanometre is one-billionth of a meter: ten times the breadth of a hydrogen molecule. The measurement of a human hair is, all things considered, 80,000 nanometres. At such scales, the customary standards of material science and science never again apply. For example, materials' attributes, for example, their shading, quality, conductivity and reactivity, can contrast significantly between the nanoscale and the full scale. Carbon 'nanotubes' are 100 times more grounded than steel however six times lighter.

Nanotechnology is hailed as having the capacity to expand the effectiveness of vitality utilization, help clean the environment, and take care of significant medical issues. It is said to have the capacity to hugely build fabricating generation at essentially decreased expenses. Eric Drexler, the researcher who begat the term nanotechnology, has cautioned of growing "amazingly intense, greatly unsafe advancements". In his book Engines of Creation, Drexler imagined that self-reproducing particles made by people may get away from our control. In spite of the fact that this hypothesis has been generally defamed by specialists in the field, numerous worries remain in regards to the impacts of nanotechnology on human and environmental wellbeing and the impact the new business could have on the North-South gap. Activists stress that the science and advancement of nanotechnology will advance speedier than strategy

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creators can devise suitable administrative measures. They say an educated open deliberation must occur to decide the harmony amongst dangers and advantages.

Nanotechnology Methods Used in Renewable and Sustainable Energy

Nanotechnology is producing a considerable measure of consideration nowadays and accordingly constructing awesome desires in the scholarly network as well as among financial specialists, the legislatures, and industry. Its one of a kind capacity to create new structures at atomic scale has just delivered novel materials and gadgets with extraordinary potential applications in a wide number of fields. Among them, critical leaps forward are particularly required in the energy segment that will enable us to keep up our expanding hunger for energy, which increments both with the quantity of individuals that join the created economies and with our request per capita.

These days, our principle energy hotspots for human movement are fossil and mineral energizes, atomic and hydroelectric sources. They are exceptionally unsafe to environment since they cause worldwide cautioning, ozone layer consumption, biosphere and geosphere pulverization, and natural obliteration.¹ Thus, the genuine energy generation can be viewed as a destructive industry both as far as contamination creation and environmental effect since the mechanical insurgency in the eighteenth century. Around 80 wt% of CO₂ emanations on the planet are begun by the energy part.

Nanotechnology offers, out of the blue, instruments to grow new ventures in light of financially savvy and cost-productive economies, along these lines genuinely adding to a practical monetary development. The utilization of nanotechnology in all the energy-related procedures that include the utilization of sunlight based radiation as an energy source. Sun oriented energy is free and fairly accessible in numerous parts around the world. In only multi year, the sun can furnish the earth with 15,000 times more energy than the atomic and fuel energy really required amid the year. This energy source can be utilized as a part of various ways: photovoltaic (PV) innovation – which straightforwardly changes over light into electrical flow, solar– warm frameworks – utilized as a part of sun based authorities, counterfeit photosynthesis – which delivers either sugars or hydrogen by means of water part, the supposed 'latent sun based' advancements, where building configuration boosts sunlight based lighting and warming, and even biomass innovation – where plants utilize the sun oriented radiation to drive concoction changes and make complex starches, which are utilized to create power, steam or biofuels

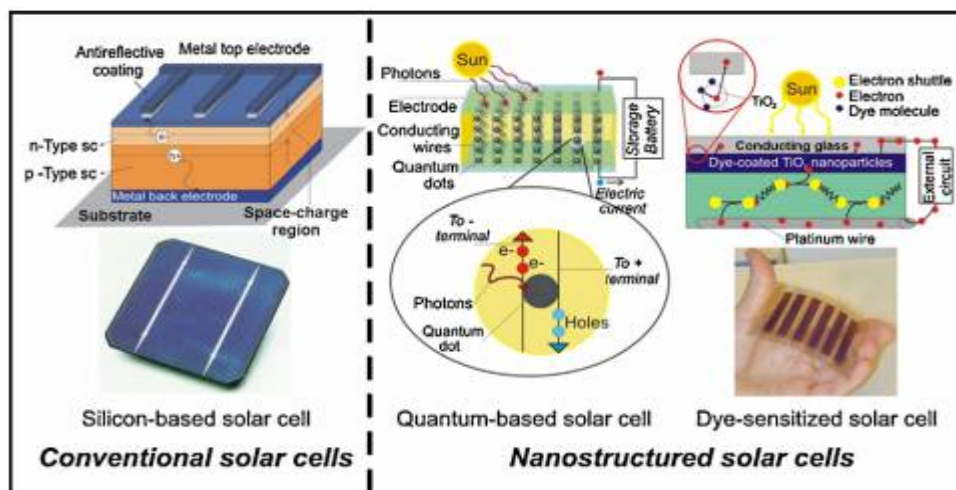


Fig . Evolution of photovoltaic technology: from conventional (silicon-based solar cells) to nanostructured solar cells (quantum-based and dye-sensitized solar cells). Adapted from Refs.

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Presently, PV advertise depends on silicon wafer-based sun powered cells (thick cells of around 150– 300 nm made of crystalline silicon). This innovation, delegated the original of photovoltaic cells, represents over 86% of the worldwide sun based cell advertise. The secondgeneration of photovoltaic materials depends on the presentation of thin film layers (1– 2 nm) of semiconductor materials. All the more particularly, they utilize thin epitaxial stores of semiconductors on cross section coordinated wafers. These cells involve around 90% of the market space yet just a little section of the worldwide PV showcase. Lamentably, in spite of the fact that a lower fabricate.

Quantum specks are productive light producers since they transmit numerous electrons per sun powered photon, with various assimilation and outflow spectra relying upon the molecule measure, accordingly remarkably raising the hypothetical effectiveness restrict by adjusting to the approaching light range. Arthur J. Nozik announced in 1982 that "a solitary edge quantum-utilizing gadget in which the energized bearers thermally equilibrate among themselves, however not with the environment, changes over sunlight based energy with a proficiency moving toward that of a vast limit gadget"².

Brinker and Ginger³ investigated the role of nanotechnology for sustainability, energy conversion, storage and conservation. They explained that energy use reduction was the main application for thermoelectricity (TE) waste heat recovery devices. These devices had a very low impact on the environment. Since, they were totally passive, clean and operated without any additional energy supply. Their use in cars and public transport systems would reduce the oil consumption. Subramani et al.⁴ presented a comprehensive review of energy minimization strategies for membrane-based desalination processes and utilization of lower greenhouse gas emission renewable energy resources.

Grebler and Nentwich⁵ displayed an article about the connection between the nanomaterials and the environment. They extricated the accompanying documentations:

- 1- Nanotechnology can be used to optimize materials.
- 2- When nanoscale carbon black added to modern automobile tires lead store inforce the material and reduce rolling resistance. This makes a fuel savings of upto10%.
- 3- Nano materials can help for self-cleaning or "easy-to-clean" coatings. For example, if they added to glass, they save both energy and water in cleaning process, since such surfaces are easier to clean or not required to be clean continuously.
- 4- Nano tribological wear protection products such as fuel or motor oil additives can reduce fuel consumption of vehicles and extend engine life.
- 5- Nanoparticles such as flow agents allow plastics to be melted and cast at lower temperatures.
- 6- Nanoporous insulating materials in the construction industry can help to reduce the energy needed to heat and cool buildings.
- 7- Nanoceramic corrosion coatings for metals without toxic heavy metals (chromium, nickel), for example in automobiles, can replace environmentally harmful or hazardous chromium (VI) layers.
- 8- Nano-scale titanium dioxide and silica can replace the environmentally damaging bromine in flame retardants

Yu and Xie⁶ condensed the ongoing advancement on the investigation of nanofluids, for example, the readiness techniques, the assessment strategies for the strength of nanofluids and the ways and systems to upgrade the

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steadiness of nanofluids. They introduced the expansive scope of present and future utilizations of nanofluids in different fields, for example, energy, mechanical and biomedical fields. They refereed in their paper, that the nanofluids were set up by the accompanying most utilizing strategies:

- 1- Two-step method: It was considered the most widely used and economic method for preparing nanofluids. Nanoparticles, nanofibers, nanotubes, or other nanomaterials used in this method were first produced as dry powders by chemical or physical methods. Then, the nano sized powder will be dispersed in to a fluid in the second processing step with the help of intensive magnetic force agitation, ultrasonic agitation, high- shear mixing, homogenizing and ballmilling.
- 2- One-step method: It consisted of simultaneously making and dispersing the particles in the fluid. In this method, the processes of drying, storage, transportation, and dispersion of nanoparticles were avoided. The one-step method can prepare uniformly dispersed nanoparticles, and the particles can be stably suspended in the base fluid

Nanotechnology makes a gigantic upheaval in the size and plan of renewable energy gadgets used for energy transformation and capacity, environmental observing, and in addition green building of environmental well disposed materials. It is demonstrated that, nanomaterials assume a huge part on the human life, by giving a cheap and clean energy which is currently turned into a worldwide industry.

III. SOLAR ALTERNATIVE FUELS

Solar energy, among all carbon-free energy sources, is viewed by some experts, as the alternative with the greatest intermediate to long-term potential to replace fossil fuels. For this to happen, however, two important challenges must be addressed. The first is providing adequate *energy storage capabilities* for solar-generated electricity, given the intermittent character of the solar resource. The second, perhaps more important challenge, is utilizing solar energy to aid in the *production of clean alternative fuels* for the transportation, industrial, and housing sectors.

Solar energy has, until now, accounted for a relatively small fraction of the overall energy supply, with its fluctuating contributions to the grid controlled and compensated by thermal generation (fossil-fuel combustion). As solar and wind penetration increases, however, the intermittency of these two energy sources seriously compromises the stability and quality of grid power. This issue has already begun to demand urgent attention in where 36.8 terawatt-hours (TWh) of electricity (equal to 6.6% of total production) was generated by solar sources in 2015. During this same period, 87.1 TWh was generated by nuclear plants, which are slated for shut down by 2021. While dependence on intermittent renewable energy sources is not yet quite so high in the India, where solar and wind accounted for 0.6 and 4.7% of overall electricity production in 2015, respectively, the relentless decline in PV module prices has continued at a rate of 5–7% annually for the past decade.

The Energy Information Administration now expects utility-scale solar generating capacity to increase by more than 60% between the end of 2014 and the end of 2016, while wind capacity is expected to increase by about 23% over the same time period. While these projections may be optimistic, and may assume the continued existence of various government subsidies, there is little doubt that generation from these intermittent energy sources will continue to show significant growth. Synthetic natural gas has three times the energy density, on a volume basis, of hydrogen. Given the central role that chemical fuels already play in electricity generation, the conversion of solar energy into chemical fuels that are capable of being used in the existing distribution and end-use infrastructure would be highly desirable.

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The higher operating temperature allows for a significant reduction in electrical power consumption (efficiencies as high as 85–90% have been reported) and for the use of non-noble metal electrodes (typically Ni-YSZ cermet cathode and a ceramic lanthanum strontium manganese oxide (LSMO) anode). Reduced ohmic and over-potential losses also allow for considerably higher current densities and more compact designs. The high operating temperatures and brittle nature of the oxide components, however, create additional challenges vis-a-vis reduced lifetimes and materials and fabrication costs. The key features of these electrolysis systems are summarized in which is taken from Herron et al Table and includes estimates of projected solar-to-H₂ conversion efficiencies, which range from 8.5% for PEM to 12% for solid oxide electrolysis cells, assuming a 15% solar-to-electricity PV conversion efficiency.

System	Operation conditions		System Efficiency	Solar-to-H ₂ efficiency (%)	Advantages	Disadvantages
	(bar)	(°C)				
Alkaline electrolysis	5–30	0–90	3–73%	10 ^a	Commercial technology low capital cost	Low current density H ₂ –O ₂ mixing
PEM electrolysis	85	100	6%	8.5 ^a	High current density Compact design H ₂ –O ₂ produced separately	High capital cost for membrane Precious metal catalyst
Solid oxide electrolysis	0	00–350	5–90%	12 ^{a,b}	High electrical efficiency Non-noble catalyst H ₂ –O ₂ produced separately	Brittle ceramics
Photo-electrochemical		5		12	High solar efficiency H ₂ –O ₂ produced separately	Degradation
Photo-catalytic		5		0.2	Simple process	H ₂ –O ₂ are mixed Low solar efficiency
Thermolysis		,200		1–2	Simple process	Low materials stability H ₂ –O ₂ : are mixed High radiative losses
Thermochemical		700	0%	18	High energy efficiency H ₂ – O ₂ produced separately	High capital cost Complex process design

Table Summary of solar-driver water splitting technologies

III. SOLAR THERMOCHEMICAL HYDROGEN PRODUCTION

Solar thermal power, or *CSP*, is an alternate means of harnessing incident solar energy that can be utilized to generate solar fuels, in addition to its more common use, in which high temperatures generated by concentrating incident solar radiation are used to drive conventional steam or gas turbines. Several routes to using CSP for solar fuel generation are discussed in the following. While thermochemical approaches are particularly promising, progress to date has been largely limited to laboratory demonstrations.

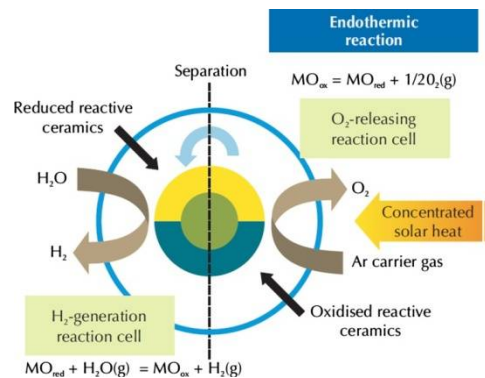
Heating water to sufficiently high temperatures to cause water molecules to split into hydrogen and oxygen or cause methane molecules to split into hydrogen and carbon by *solar thermolysis* requires temperatures above 2200 °C. This two-step process eliminates the need for high-temperature gas separation of, for example, the H₂ and O₂ formed during water thermolysis, and allows coordination with the daily solar cycle (the reduction step can occur during daylight, the re-oxidation step during the evening). Alternatively, the two steps can be separated spatially by delivering the deoxidized materials where the hydrogen is needed, e.g., at refueling stations or chemical plants, thereby achieving higher volumetric energy densities than are available with compressed hydrogen. Theoretical solar-to-fuel efficiencies as high as 35–50% have been estimated, but these assume high rates of fuel production and a high level of heat recovery. A recent analysis suggests that a solar-to-methanol system that achieved 7.1% efficiency with H₂O and CO₂ as feedstocks would result in methanol's price being competitive with that of other renewable-resource-based alternatives,

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Solar-driven, two-step water splitting to form hydrogen based on reduction/oxidation reactions

While the solar *thermochemical* process provides a clean, efficient, and sustainable route for producing hydrogen from water, challenges include reducing heat losses during each step of the process cycle, scaling up and improving the coupling of the solar concentrators to the reactors, identifying appropriate reactor containment materials and seals, and ensuring that the working materials continue to allow for rapid reduction and oxidation during the cycling process even after many thermochemical cycles.

Carbon dioxide-derived fuels

The earth is going through a rapid period of warming due to high levels of global CO₂ emissions from human activity (34 billion tons in 2011). CO₂ concentrations in the atmosphere are still low enough (0.04%) that it would be impractically expensive to capture and purify CO₂ from the atmosphere. But other sources of CO₂ are available that are considerably more concentrated. Power generation based on natural gas or coal combustion is responsible for the major fraction of global CO₂ emissions (including 38% of overall emissions in the India), with other important sources being represented by the cement, metals, oil refinery, and petrochemical industries. Nearly, 8000 large, stationary sources of CO₂ exist worldwide, each with annual CO₂ emissions above 0.1 Mt. Indeed, a growing number of large-scale power plant *carbon dioxide capture and storage* (CSS) projects are either operating, under construction, or in the planning stage, some of them involving facilities as large as 1200 MW capacity.

While solar PV energy conversion has the potential to reduce CO₂ emissions by serving as an alternative means of generating electricity, harnessing solar energy to convert the CO₂ generated by other sources into useful fuels and chemicals that can be readily integrated into existing storage and distribution systems would move us considerably closer to achieving a carbon-neutral energy environment. This section reviews options for CO₂ capture and separation.

Herron et al., in a very recent review, examine the main routes for CO₂ capture from stationary sources with high CO₂ concentrations derived from *post-combustion*, *pre-combustion*, and *oxy-combustion* processes. In *post-combustion*, flue gases formed by combustion of fossil fuels in air lead to gas streams with 3–20% CO₂ in nitrogen, oxygen, and water. Other processes that produce even higher CO₂ concentrations include *pre-combustion* in which CO₂ is generated at concentrations of 15–40% at elevated pressure (15–40 bar) during H₂ enrichment of synthesis gas (syngas) via a water–gas shift reaction and *oxy-combustion* in which fuel is combusted in a mixture of O₂ and CO₂ rather than air, leading to a product with 75–80% CO₂. CO₂ capture can be achieved by absorption using liquid solvents (wet-scrubbing) or solid adsorbents. In the former approach, physical solvents (e.g., methanol) are preferred for concentrated CO₂ streams with high CO₂ partial pressures, while chemical solvents [e.g., monoethanolamine (MEA)] are useful in low-pressure streams. Energy costs for MEA wet-scrubbing are reportedly as low as 0.37–0.51 MWh/ton CO₂ with a loading capacity of 0.40 kg CO₂ per kg MEA. Disadvantages of this process are the high

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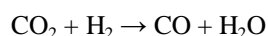
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energy cost for regenerating solvent, the cost to compress captured CO₂ for transport and storage, and the low degradation temperature of MEA.

Alternatives include membrane and cryogenic separation. With membranes, there is an inverse correlation between selectivity and permeability, so one must optimize between purity and separation rate. Cryogenic separation insures high purity at the expense of low yield and higher cost. Currently, MEA absorption is industrially practiced, but is limited in scale: 320–800 metric tons² CO₂/day (versus a CO₂ generation rate of 12,000 metric tons per day for a 500 MW power plant). Scale-up would be required to satisfy the needs of a solar refinery. Alternatives, such as membranes, have relatively low capital costs, but require high partial pressures of CO₂ and a costly compression step to achieve high selectivity and rates of separation. Indeed, since carbon capture reduces the efficiency of power generation, power plants with carbon capture will produce more CO₂ emissions (per MWh) than a power plant that does not capture CO₂. Therefore, the cost of transportation fuel produced with the aid of CO₂ capture must also cover the incremental cost of the extra CO₂ capture. These costs must then be compared to the alternative costs associated with large-scale CO₂ sequestration, the practicality of which also remains to be demonstrated. Finally, one also needs to consider the longer term rationale for converting CO₂ to liquid fuels once fossil-fuel power plants cease to be major sources of CO₂. Closed-cycle fuel combustion and capture of CO₂ from, e.g., vehicle tailpipes, present a considerably greater technical and cost challenge than capture from concentrated stationary sources.

CO₂ can be converted to fuels with renewable, solar-derived hydrogen and solar heat, as discussed above. For example, the reverse-water–gas shift reaction (RWGS):



can be used, in concert with catalysts (copper-, iron-, or ceria-based systems), to convert CO₂ and hydrogen to CO and water. The CO mixed with hydrogen produces syngas, which can be used to generate a variety of products, including methanol, or liquid hydrocarbons through Fischer–Tropsch synthesis. Issues related to the thermal stability of the catalysts and the undesired formation of methane still need to be resolved. There are also direct routes for hydrogenating CO₂ to make products including methanol, methane, and formic acid. Besides these hydrogenation routes, CO₂ can also, in principle, be converted to fuels using direct solar energy through electro-catalytic, photo-electrochemical, and thermochemical reduction, although these approaches remain in very early stages of development.

IV. SOLAR ENERGY BASED IEC RESULTS

The sustainable nature of solar electricity along with its associated large resource potential and falling costs have motivated a rapid increase in the deployment of utility-scale solar electricity generation plants in recent years. As the installed capacity of photovoltaics (PVs) continues to grow, cost-effective technologies for solar energy storage will be critical to mitigate the intermittency of the solar resource and to maintain stability of the electrical grid. Hydrogen generation via solar water splitting represents a promising solution to these challenges, as H₂ can be stored, transported and consumed without generating harmful byproducts. However, the cost of H₂ produced by electrolysis is still significantly higher than that produced by fossil fuels. The Department of Energy has calculated the H₂ threshold cost to be \$2.00–\$4.00 per gallon of gasoline equivalent⁹, whereas the most up-to-date reported H₂ production cost via electrolysis is \$3.26–\$6.62 per gallon of gasoline equivalent. There are several promising approaches to large-scale solar water splitting, including photochemical, photoelectrochemical (PEC) and PV-electrolysis systems; none of these approaches are currently economically viable compared with today's technologies.

To be practical for large-scale deployment, the cost of solar H₂ generation must be significantly reduced. Previous studies have predicted that achieving a high solar-to-hydrogen (STH) efficiency is a significant driving force for reducing the H₂ generation cost. To date, the highest efficiency demonstrated using a PEC water splitting system with at least one semiconductor–liquid junction is 12.4%. Theoretical studies using a variety of assumptions have predicted that the maximum attainable efficiency using a tandem PEC water splitting device is 23–32%. PV-electrolysis systems have demonstrated exceptional potential to achieve even higher STH efficiencies.

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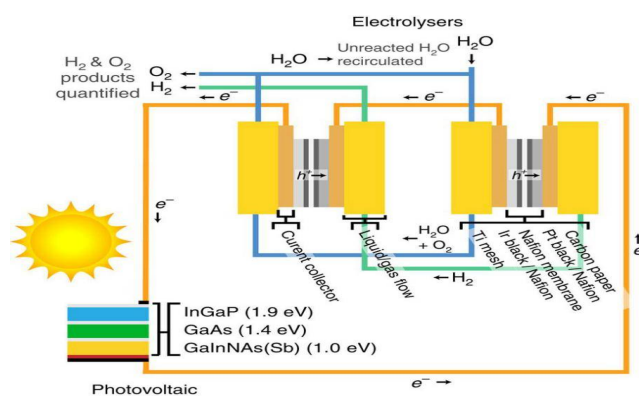
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In this work, we employ a high-efficiency triple-junction solar cell with two series-connected polymer electrolyte membrane (PEM) electrolyzers to achieve very high STH efficiency. Our system produces H₂ with a 48 h average STH efficiency of 30%, the highest efficiency reported to date for any solar H₂ production system, to the best of our knowledge. This work demonstrates the potential for building extremely high-efficiency solar H₂ production systems using current state-of-the-art commercially available solar cells and laboratory PEM electrolyzers. The device design presented herein could provide a viable route to implementing large-scale solar water splitting installations.

PV-electrolysis system design

A schematic of the PV-electrolysis system is shown. The solar cell is a commercially available triple-junction solar cell manufactured by Solar Junction, with an active area of 0.316 cm². From top to bottom, the three subcells of the PV are made of InGaP ($E_g=1.895$ eV), GaAs ($E_g=1.414$ eV) and GaInNAs(Sb) ($E_g=0.965$ eV) respectively. The cell was installed on a water-cooled stage, which maintained a cell temperature of $\sim 25^\circ\text{C}$ and was illuminated with white light from a xenon arc lamp to simulate concentrated AM 1.5D solar illumination. (for comparative xenon arc lamp and AM 1.5D spectra.) The two PEM electrolyzers consist of Nafion membranes coated with 0.5 mg cm⁻² Pt black catalyst at the cathode and 2 mg cm⁻² Ir black catalyst at the anode. The two electrolyzers were connected in series with the PV cell and a potentiostat, which was used to measure the current through the circuit. Water was pumped into the anode compartment of the first electrolyser, whereas the cathode of the first electrolyser had no input flow. The water and O₂ effluent from the first electrolyser's anode compartment flowed into the anode compartment of the second electrolyser. Likewise, the H₂ from the cathode side of the first electrolyser flowed into the cathode side of the second electrolyser. The H₂ and O₂ products flowing out of the second electrolyser were collected and quantified, whereas the unreacted water was fed back into a water reservoir and recycled through the system. The temperature of the electrolyzers was held at $\sim 80^\circ\text{C}$, consistent with standard operating conditions for industrial water electrolyzers. The system operated continuously for 48 h without interruption. Further details of the experimental setup are included in the Methods section.

Figure 1: PV-electrolysis device schematic.



The PV-electrolysis system consists of a triple-junction solar cell and two PEM electrolyzers connected in series.

System performance

The $I-V$ characteristics of the cell under both 1 sun and concentrated illumination. Following a standard method for characterizing concentrated PV cells, we used the ratio of the short circuit currents to calculate that the cell was illuminated with 42 suns white light under the concentration condition. At the maximum power point, the cell voltage (V_{MPP}) output is 2.91 V and the current density (J_{MPP}) is 565.9 mA cm⁻². The measured solar-to-electricity efficiency is 39% under these operating conditions. The $I-V$ characteristics of the dual electrolyser and the solar cell, measured before and after the 48 h operation, are shown.

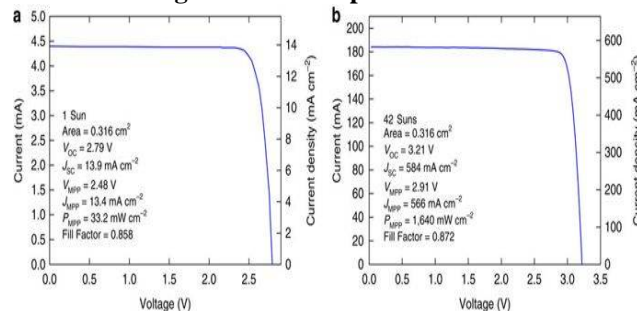
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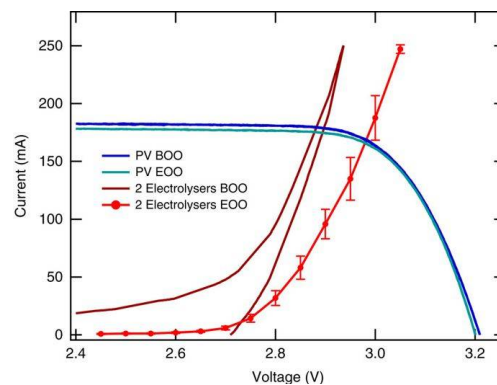
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Figure 2: PV cell performance.



The I - V characteristics of the triple-junction solar cell under (a) 1 sun and (b) 42 suns, which is the illumination concentration used for the 48 h electrolysis. The key performance parameters are included in the figure. I - V curves were collected using both forward and backward voltage sweeps. These measurements generated identical results; thus, this figure shows only the forward sweep results.

Figure 3: PV cell and PEM electrolyser performance at the beginning and end of operation.



The I - V characteristics of the triple-junction solar cell and the dual-electrolyser at both beginning-of-operation (BOO) and end-of-operation (EOO). The blue and cyan curves are the solar cell I - V curves under 42 suns at BOO and EOO, respectively. The dark and light red curves are the I - V curves of the dual-electrolysers at BOO and EOO, respectively.

STH efficiency

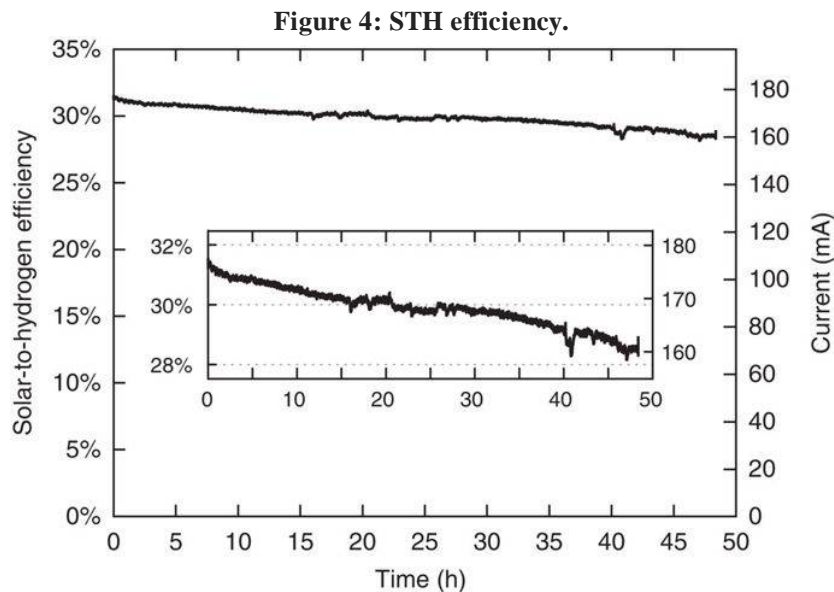
The electrolysis current and the corresponding STH efficiency through the 48 h experiment. The operating current decreased by only 10% over this period from an initial value of 177 mA to a final value of 160 mA. The STH efficiency was calculated by multiplying two times the thermodynamic potential (V_{redox}), the electrolysis current (I_{WE}) and the Faradaic efficiency for hydrogen evolution (η_{F}), then dividing by the input light power (P_{in}).

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In this system, the thermodynamic potential for the water-splitting reaction is 1.18 V, as the dual electrolyser was operating at 80 °C. A P_{in} value of 1,328 mW was obtained by multiplying the operational concentration (42 suns) by the 1 sun illumination intensity (100 cm^{-2}) and the solar cell area (0.316 cm^2).

V. CONCLUSION

This would allow both the production of biofuel and electricity from the one facility making efficient use of available land. We propose introducing a filter above the algae pond that will allocate the incident illumination to different purposes. The study have modelled this by using commercially available lighting filters as *blackbox* filters.

This hypothetical filter allows the transmitted light through to the algae and used the remainder to generate electricity using either a highly efficient crystalline silicon solar cell or an amorphous silicon solar cell. Using this system up to 151 W.m^{-2} of electrical power can be produced. Introducing a method of cogeneration of electrical energy has benefits in the often remote areas microalgae cultivation occurs. This can result in a total available PAR of 177 W.m^{-2} which can be used to increase the productivity and value of algae cultivation. The results of the Faradaic efficiency measurements and calculations indicate that the electrolyser is selective for producing H_2 and O_2 . We assume that our system has nearly 100% Faradaic efficiency for hydrogen production, consistent with other studies of PEM electrolyzers. Further details about the product quantification measurements and procedure for STH calculations are provided.

The average STH efficiency achieved over the entire 48+ h of operation was 30%. The decrease in STH over 48 h of operation is mainly due to an increase of V_{OP} over the maximum power point primarily caused by a decrease in performance of the electrolyzers over time, an issue that is readily addressable through electrolyser development, as commercial electrolyzers have demonstrated tens of thousands of hours of stable operation. Although electrolyser performance accounts for most of the decrease in PV-electrolysis efficiency over time also shows that the current of the solar cell was slightly lower at the end of operation compared with the beginning of operation, which is due to a slight decrease of the incident light intensity. This contributed approximately one percentage point to the total STH loss, as the STH calculation was performed using the initial incident light intensity; thus, the overall STH efficiencies reported are conservative values.

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VI. DISCUSSION

The efficiency analysis assumes that the light incident on the PV cell is the only energy input into the system. In reality, there can be additional energy inputs, including the energy required to cool the PV, heat the PEM electrolyzers and pump water into the electrolyzers. In a concentrated PV device illuminated by natural sunlight, there may also be optical losses in the lenses or mirrors used to concentrate the incident sunlight onto the PV cell, which could reduce the system efficiency. We have chosen to neglect these factors in this study for several reasons, among them to allow for direct comparisons with results from previous studies. We note in general that laboratory-scale systems are designed differently than commercial-scale systems and the losses are not identical. For instance, in this study, lenses or mirrors were not needed to achieve the simulated concentrated solar light; thus, there are no optical losses to measure. In addition, commercial-scale PV systems and PEM electrolyzers have been designed to minimize energy losses involving cooling, heating, pumping and so on; thus, the losses in a laboratory-scale demonstration system are less relevant, in addition to being more difficult to accurately quantify. Ultimately, the methods used to supply the aforementioned additional energy inputs in a laboratory-scale system are not optimized; thus, they are not an accurate representation of what could be achieved in large-scale PV-electrolysis systems.

Appropriate designs will minimize the heating, cooling and pumping energy inputs. If needed, additional heat could be supplied by the sunlight that is not converted to electricity. It might also be desirable to operate the PV at a temperature $>25^{\circ}\text{C}$. Although this would decrease the PV's open circuit voltage, it would increase the current output and decrease the energy input needed to cool the PV (if active cooling methods were employed). This could result in an increased STH efficiency if the PV still produced enough voltage to drive the dual-electrolyser. The PV operating temperature and other operation parameters pose tradeoffs to be optimized. Overall, the system design and operating conditions must be chosen to minimize the levelized cost of hydrogen produced over the operating lifetime of the system. Technoeconomic models of large scale, centralized solar H_2 production facilities suggest that achieving high STH efficiency is one of the most important factors in reducing the cost of H_2 , potentially even more important than reducing the cost of the absorber or catalyst materials. Continued development of lower cost, higher efficiency PV cells and electrolyzers, optimized PV-electrolysis system designs and technoeconomic models to predict hydrogen costs are all important subjects for continuing research. In summary, we report a PV-electrolysis system that demonstrated an average STH efficiency of 30% over a 48 hr period of continuous operation. This is the highest STH efficiency reported to date and the first solar water splitting system that demonstrates a STH efficiency reaching 30% or higher. Coupling a high-efficiency multi-junction solar cell with two electrolyzers in series is an effective way to minimize the excessive voltage generated by a multi-junction solar cell, allowing for greater utilization of the high-efficiency PV for water splitting. The demonstration of this high-efficiency system is an important step closer to the US Department of Energy technology and cost goals, and shows great opportunities for solar energy storage and H_2 production with solar water splitting.

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International Journal of Innovative Research in Science, Engineering and Technology

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